

Approved For Release STAT  
2009/08/17 :  
CIA-RDP88-00904R000100100

Dec

Approved For Release  
2009/08/17 :  
CIA-RDP88-00904R000100100



**Third United Nations  
International Conference  
on the Peaceful Uses  
of Atomic Energy**

A/CONF.28/P/339  
USSR

May 1964

Original: RUSSIAN

Confidential until official release during Conference

*File*

**STUDY OF TENDENCY TO BRITTLINESS OF FERRITE-  
PEARLITE STEELS FOR REACTOR VESSELS DURING  
NEUTRON IRRADIATION**

A.D.Amayev, P.A.Platonov,  
N.F.Pravdyuk

**I. INTRODUCTION**

The present study deals with radiation embrittlement and the effects of neutron spectrum on mechanical property changes of various steels following the irradiation, and was issued by the "hot" metallographic laboratory of the I.V.Kurchatov Institute of Atomic Energy.

The materials under study were steels as represented in Table I.

The samples were irradiated in the RFT reactor.

The integral flux is defined through the activation of threshold foils (sulphur and nickel) and also by making use of the calculation means proceeding from the capacity of the channel where the sample irradiation took place. The irradiation temperature transpired through the diamond indicators. Herein the report covers the integral fluxes as to the neutrons of the more than 1 Mev energy.

**EFFECTS OF IRRADIATION ON THE PROPERTIES  
AT EXTENSION**

Fig.2 represents the changing of yield strength at 20°C of various steels and their welded joints depending on the dose and temperature of irradiation.

The yield strength changes of the 22K steel irradiated by the fluxes up to  $10^{18}$ - $10^{20}$  n/cm<sup>2</sup> are well described by means of the linear function of the irradiation dose in the units  $10^{18}$  n/cm<sup>2</sup> ( $E > 1$  Mev) in the power 1/3.

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The shift of the straight lines to the right from the origin of coordinates indicates that in the range of a comparatively small integral flux (below  $10^{18}$  n/cm<sup>2</sup>) the yield strength surplus comes as it seems, under a different regularity.

For the steels under the study the dependence of yield strength surplus with the latent period very well in the count is describable for the doses above  $10^{18}$  n/cm<sup>2</sup> through the equation:

$$\Delta \sigma = A [(\phi t)^{1/3} - (\phi t_0)^{1/3}] \quad , (1)$$

where A stands for a coefficient dependent on the material and irradiation conditions,  $t_0$  being the integral dose in conformity with the latent period which in the current experiments makes about  $4 \times 10^{16}$  n/cm<sup>2</sup>.

Fig.2 gives the data for various irradiation conditions. The view was held that the yield strength changes observe the law (1). Table 2 gives the coefficient values for different materials and irradiation conditions. It transpires from the above data that the very same steel comes under a clear-cut regularity of the yield strength changes. There are a few (at least, 2 or 3) ranges of temperatures where the irradiation brings about different effects. In the low carbon steel and its welded joints in the range of temperatures from 100-265° the defects seem to come to the fore of the same kind since this range of temperatures does not include basically different radiation strengthening changes.

In the steels 16PHM and 25X3HM of the low-alloy type the radiation strengthening effect is comparable with mild steel strengthening. The high-strength steels of the 12H2MFA and 25H2MFA types (3) are less subject to the effects of irradiation than low-carbone ferrite and perlite steels.

Fig.3 shows the effects of the temperature of testing on the yield strength and regular elongation of steel 22K before and after the irradiation. The 20-350° testing showed that the yield strength and regular elongation of the irradiated samples is sensitive to the testing temperature.

The 150° testing as compared to the temperature of 20°C leads to lower yield strength of the irradiated samples, the changes in regular elongation being insufficiently small. At 250 degrees the regular elongation is more sensitive to testing temperatures than the yield strength. In the range of testing temperatures 250 - 300° a jump in sample properties changing occurs irradiated at 185°. The conditions of Fig.3 as regards the irradiation and temperature of testing, provide for a higher yield strength of irradiated samples and lower regular elongation than in non-irradiated samples. It needs to consider the general process of properties changes in relation to the temperature of testing to discover that the higher the irradiation temperature the more stable the properties in relation to the temperature of testing. This is indicative of the formation of more persistent radiation defects at higher irradiation temperatures, which offer a great deal of resistance to the moving dislocations even at higher temperatures.

As it comes from Fig.3 for the samples irradiated at the temperature 185° before the annealing temperature of 250° there will be no considerable changes in properties. In the temperature range of about 275° the annealing starts up, yet it takes up the most intensive forms within the temperature range of 300°-350°. The full recovery of plastic and strength properties occurs at the temperature of 400-450°.

Raising irradiation temperature to 285° causes a shift of the initial point of the recovery of properties toward the range of higher temperatures; the annealing begins in the temperature range from 300-350° and the full recovery of the yield strength and regular elongation is laid in the area of 450 - 500°.

In the samples irradiated at the temperature of 350° the yield strength reverse movement begins within the range of 350 - 400°, its being 400-450° for regular elongations. The full property recovery takes place within the range of 500-550°. (The annealing time was 15 min and at 400° it was 180 min).

Thus the radiation defects are annealed within a wider range of temperatures (275-550°). The temperature being very much the same, it is observed that yield strength recovery differs from that of the regular elongation (especially at abnormally high temperatures of irradiation - 285° and 350°).

The recovery of steel samples properties irradiated at 185° on the earlier annealing stage than in the case of higher temperature samples reveals the formation of defect groups of different complexity responsible for the changes of mechanical properties.

#### EFFECTS OF IRRADIATION ON THE CRITICAL TEMPERATURE OF BRITTLENESS

As a critical temperature for cylindrical samples the temperature was used where the impact ductility value constitutes 0.4 of its maximal value, while for the Menager samples the evaluation took place of the fibrous fracture area.

Fig.4 depicts the surplus of critical temperature of brittleness in relation to the integral neutron flux for various steels and their welded joints. This covers the data obtained from the samples subjected to the pre-irradiation artificial ageing. The irradiation from  $10^{18}$  to a few units of  $10^{20}$  n/cm<sup>2</sup> indicates that as far as the low carbon and low alloy steels are concerned and their welded joints, the surplus of the critical temperature of brittleness may be described by the expressions:

$$\Delta T = 22.5 + 55 (\phi t)^{1/3}, ^\circ\text{C} \quad (2)$$

where  $\phi t$  represents the integral flux in the units of  $10^{18}$  n/cm<sup>2</sup> ( $E > 1$  Mev).

The difference in B factor values owes itself primarily to the high sensitivity of impact ductility towards the steel's structure, composition, strength and plasticity. Minor structure alterations do not affect the static properties but have an outspoken effect on the impact proper-

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ties even without any transition to other types of destruction. On the other hand, this exaggerated sensitivity constitutes a merit of the impact testing as a method of appreciating the irradiated steels' properties inclined to cold brittleness.

Fig.5 illustrates that for the same steel the surplus of the critical temperature of brittleness after the irradiation within the dose range from  $10^{18}$  to  $10^{20}$  n/cm<sup>2</sup> is proportional to the integral flux in the power 1/3 i.e.

$$\Delta T = B \left[ (\phi t)^{1/3} - (\phi t_0)^{1/3} \right], \text{ } ^\circ\text{C}$$

where B - is the coefficient dependent on the material and irradiation conditions (Table II);

$\phi t$  - is the integral flux in the units  $10^{18}$  n/cm<sup>2</sup>  
( $E > 1$  Mev);

$\phi t_0$  - is the value never in excess of  $8 \times 10^{15}$  n/cm<sup>2</sup>  $\times 10^{-18}$ .

If compared the data of Fig.1 and 5 show that the alterations in the critical temperature of brittleness and yield strength are subordinate to the same regularity.

The effect of the irradiation temperature (from 130° to 450°) on the surplus of the critical temperature of brittleness for various steels is represented in Fig.6. The curves were drawn on the separate experimental points by making use of the formula (3).

It follows from the data in Table II that in the temperature irradiation range of 130°-265° the ratio of the coefficients  $\frac{B}{A}$  makes  $3 \pm 0.2 \left[ \frac{^\circ\text{C}}{\text{kg} \times \text{mm}^{-2}} \right]$ .

As long as the irradiation temperature rises the ratio goes down to approximately 1.2 for the temperature of irradiation at 450°. This drop can be accounted for by a very considerable plasticity change at higher irradiation temperatures, while the strength rises.

Table II data and Fig.6 show that low-carbon and low-alloy steels following the irradiation acquire different tendency to brittleness. The harder the steel in its initial state, the less the surplus of the critical temperature of

brittleness. Yet, in the low-alloy steel 16ГНМ the tendency to brittleness through the irradiation is very much like that in the low-carbon steels and its welded joints.

The process of ageing goes parallel to lowering plasticity and, above all, impact ductility. It was, therefore, of interest to follow how the irradiation affects "normally" processed and artificially age-hardened low-carbon steel.

At static bending depending on the inclination to brittleness, various steels yield the curves of bending with different positions of "slump" chiefly.

The critical temperature of brittleness ( $T_{1/3}$ ) the maximal temperature where the slump sum totals ( $\Delta P_1 + \Delta P_2 + \dots + \Delta P_5$ ) or the single slump value makes no less than one third of the maximal loading, i.e.

$$\frac{\sum \Delta P_i}{P_{\max}} \geq \frac{1}{3}.$$

The relative slump value  $\frac{\sum \Delta P_i}{P_{\max}}$  resulting from the

"load-deflection" diagrammes for the sharp notch samples (10 x 10 x 55 and 20 x 20 x 110 mm) as well as those with reproduced cracks (10 x 10 x 55 mm) depending on the temperature of testing is given in Fig. 7.

It is clear that in a low-carbon steel of the 22K type the ratio  $\frac{\sum \Delta P_i}{P_{\max}}$  is sensitive to the temperature of testing, and the straight lines for the transition of material from the ductile  $\frac{\sum \Delta P_i}{P_{\max}} \% = 0$  to brittle state

( $\frac{\sum \Delta P_i}{P_{\max}} \% = 100$ ) covers the range of temperatures not more than  $30^\circ$ . This temperature range tends to narrow in the samples with reproduced cracks and of a larger size. In the non-irradiated samples the outcomes of sensitivity toward the crack find their expression in a temperature rise of  $10^\circ$  above the critical temperature of brittleness.

The larger size of the samples (20x20x110 mm instead of 10x10x55 mm) causes an increase of  $T_{1/3}$  by  $30^\circ$ .

One of the reasons behind the effects of the sample size on the critical temperature of brittleness might appear to be the system's elastic energy (that of machines, gears

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and samples) at the moment of slump formation. In the supercritical region of loading the system's large elastic energy plays to substantially accelerate the starting destruction process, for the final results are affected not only by the material properties, but also the system's elastic energy.

The bending diagramme analysis showed that the ratio of elastic energy at the initial moment of destruction to the notch area of the sample under testing in the sample 20 x 20 x 110 mm exceeds that in the sample 10 x 10 x 55 mm by 35%.

As it transpires from Table III, the critical temperature of brittleness depends on the notch shape and sample size. Simultaneously, it should be emphatically said, that for the same material a shift of the critical temperature of brittleness for various samples and testing methods diverges by 20% at most from the results represented in the Table.

Thus, larger sample sizes and notches of extreme sharpness (reproduced crack samples) do not result in a higher surplus of the critical temperature of brittleness for the 22K type steel as compared with the surplus of the samples of standard size and notch.

The authors hold the view, however, that the work dealing with the study of the sample size effects on the inclination to brittleness of the irradiated steels designed for reactor vessels is to be carried on unless it is probable that further sample size increase and integral irradiation dose might bear qualitatively novelty fruit.

The alterations in the steels mechanical properties because of irradiation are reversible (1.3) if no microstructural changes occur in the process of irradiation or else if there are no great number of new impurities bearing heavily on the altering properties.

The effect of annealing on the impact properties of the irradiated samples of weld metal with "normal" processing as well as those after artificial ageing has shown that, in the artificially aged samples of weld metal

after irradiation and annealing the process of impact property recovery is by far more intensive than in the normally processed samples. For the first type samples it suffices to anneal them at  $300^{\circ}$  during 3 hours to recover their impact properties fully, whereas it takes the  $350^{\circ}$  temperature to anneal the samples with normal processing.

It must be mentioned that in the artificially aged samples the  $300^{\circ}$  heating for as long as 3 hours results in the recovery of those changes which were due to the irradiation. The changes because of the deformational ageing persist after the heating by  $300^{\circ}$ .

It follows that the hardening due to the deformational changes are overlapped by radiation hardening.

The data of impact and static bending tests of the irradiated and annealed samples are suggestive of complicated steel structure processes.

It was established that the temperature and irradiation dose increases lead to annealing temperature increase needed for the recovery of steel impact properties. For example, in the steel 22K the dose increase from  $10^{19}$  n/cm<sup>2</sup> up to  $2.10^{20}$  n/cm<sup>2</sup> decreases the recovery of impact properties from 90-100 per cent to 60-70 per cent at annealing by  $300^{\circ}$  after the irradiation at  $185^{\circ}$ ; the annealing at  $400^{\circ}$  recovers the sample impact properties only by 20-30 per cent, irradiated at  $350^{\circ}$  in the flux of  $2.5.10^{20}$  n/cm<sup>2</sup>.

It is evident that the observed general regularities of separate mechanical properties changes depending on the irradiation dose and temperature are very well in existence. The most close is the correlation in the case of yield strength and critical temperature of brittleness. The differences in initial properties play, however, as well as the physical nature of these materials, to make these regularities put on different forms for different steels.

#### INFLUENCE OF THE NEUTRON SPECTRUM ON THE STEEL MECHANICAL PROPERTIES

It has been attempted of late to consider the influence of the neutron spectrum as reflected in the comparison of the experimental results to have been obtained in various

reactors (4,5,6,7). These attempts are based primarily on the calculations of the rate of pair defects emergence under the irradiation in various spectra. In this case either the defect emergence rate (5) or the loss of energy by fast neutrons at elastic collisions with the nuclei of the material under irradiation are assumed to be the damage criterion (6). Zeeger (9) proceeded with the theory of radiation strengthening based on the idea of the so-called "depleted zones" which mostly add to the yield strength component because of the "friction" tension in the dislocation movement. According to this model, the yield strength must increase proportionally to the square root of the integral neutron flux.

It looks utterly possible, that on the basis of this model certain parameters can be obtained helpful in predicting the material behaviour in any neutron spectrum.

To make the problem look more detailed the calculation will be carried on for iron (or mild steel) workable in the temperature range where isolated point defects permit annealing, yet, the strengthening is practically independent of temperature. This conforms to the temperature interval of approximately 100°-250°C.

To consider the relations between the strengthening in irradiation conditions and the fast neutron spectrum it needs making the following suggestions:

- a) the strengthening owes itself to depleted zones because of cooperative focused collisions with the mass transfer;
- b) the energy interval of recoil atoms where depleted zones are likely to come into being, coincides with that where the recoil atom's range is equal to the interatomic distance (i.e. the interval of displacement spike). The neutron energy in conformity with the minimal and maximal energy of the recoil atom in this interval will be referred to as the lower and upper threshold energies ( $E_1$  and  $E_2$ );
- c) the non-focussed and the simple pair collisions result in the isolated point-effects to be annealed and never to participate in metal strengthening;

d) the yield strength changes couple with the saturation conditioned by the focuson vacancy captures with mass transfer.

The vacancy build up equation centered in the depleted zones could be written down, slight approximation coming in, in the following way:

$$\frac{dn}{dt} = a\bar{v} - a\beta h, \quad (4),$$

where  $a$  is the number of collisions of fast neutrons with the material atoms per a unit of time,  $\bar{v}$  - the mean focuson number with the mass transfer by a single collision,  $\beta$  - the probability of the focuson capture by a vacancy calculated for the concentration of vacancies  $1, \text{cm}^3$ .

Integrating (1), obtain

$$n = \frac{1}{\beta} (1 - e^{-a\bar{v}\beta t}) \quad (5)$$

Since, in accord with the initial suggestions,  $n$  - is the number of vacancies in  $1 \text{ cm}^3$ , concentrated in depleted zones and the number of these zones is on the parity with that of primary displacements, the mean size of depleted zone can be expressed:

$$\bar{x}_0 = \left\{ \frac{6}{\beta} \frac{V_0}{a\beta t} [1 - e^{-a\bar{v}\beta t}] \right\}^{1/3} \quad (6)$$

where  $V_0$  is the vacancy volume.

Since the increasing of yield strength  $\Delta \sigma \approx A_1 \cdot 1/\Lambda$ , where  $\Lambda$  is the average distance between the depleted zones in the plane of sliding and, in its turn,

$$\Lambda = (\text{at } x_0) - \frac{1}{2} \quad (7)$$

then

$$\Delta \sigma \approx A_1 \int \frac{6}{\beta} \frac{V_0(\text{at})^2}{\beta} [1 - e^{-a\bar{v}\beta t}] \quad (8)$$

It would not be hard to notice that the yield strength changes at smaller irradiation doses is proportionate to  $t^{1/2}$ , at larger ones - is proportionate to

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 $t^{1/3}$  which is in a qualitative agreement with the experimental data. Some of the values to enter the equation (5) are available from the fundamental considerations, some - to be derived from the experiment. The number of collisions per a time is evidently equal

$$a = \int_0^\infty \Sigma_t p(E) \psi(E) dE \quad (9)$$

where  $\Sigma_t$  - transport cross-section of neutron scattering,  
 $\psi(E)$  - neutron flux.

If it is suggested that from the starting point of depleted zone the focusons with the mass transfer spread around isotropically and the average range is  $\rho$  the probability of focuson absorbtion looks like the following, the defect concentrations being relatively low  $\beta = b^2 \rho$  where  $b^2$  - is the geometrical cross-section of the vacancy.

The value  $\rho$  can be determined on the basis of the data of dependence of  $\Delta G$  on the irradiation dose. One might get the idea that saturation and, therefore, deviation from the linear dependence of  $\Delta G$  on  $(\psi t)^{1/2}$  is not available until the spheres of the radius drawn around the centers of depleted zones are not overlapped, then

$$\rho = (at_0) - \frac{1}{3}, \quad (10)$$

where  $t_0$  is the irradiation time corresponding to the outset of the deviation from the linear dependence.

Clearly, that the constants  $b^2$  and  $\rho$  are independent of the spectrum and stand out as the characteristics of material.

So, the neutron spectrum influence is determined in terms of the values  $a$  and  $\bar{\nu}$ . The value  $\bar{\nu}$  as it appears from equation (8) might be defined also immediately from the curve of the dependence of  $\Delta G$  on the irradiation dose by way of determining the exponent.

In order to determine the value  $\bar{\nu}$  for the other spectrum it may be reasonably suggested that the focused collision with mass transfer alongside with the emergence of depleted zone calls for some average energy  $\bar{E} \psi$ . Then the average number of focussed displacements resulting from

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a single collision with a neutron assumes the form:

$$\bar{V} = \frac{E_1 \int_{E_1}^{E_2} \sum_{F_1} \text{tr}(F) \psi(F) \mathcal{L} E \mathcal{L} E + \mathcal{L} E_2 S_{E_2} \sum_{F_1} \text{tr}(F) \psi(F) \mathcal{L} E}{\bar{E} \phi \int_{E_1}^{E_2} \sum_{F_1} \text{tr}(F) \psi(F) \mathcal{L} E} \quad (11)$$

where  $\mathcal{L} \approx 2M/(M+1)^2$  (M is the mass of the target atom).

As an example, the study was carried out of the curve of the yield strength changes for a mild steel as regards the irradiation dose in the PQT reactor core. The neutron spectrum in the reactor core of the PQT reactor is given in Fig.8(1)<sup>x)</sup>. It has come to the surface after analysing the yield strength that the experimental points locate in a pleasing manner on the dependence calculated after the equation (5) (with the degree of precision up to the constant multiplier  $A_1$ ), Fig.15 bearing very well to this effect. The calculations led to the following parameter values:  $\rho = 1.7 \times 10^{-6}$  cm,  $\bar{V} = 120$  and  $E \phi = 64$  ev, for  $E_1$  and  $E_2$  values, were chosen respectively, 20 kev and 1 Mev which are in close correspondence with the threshold values after Brinkman (13). The values  $\rho$ ,  $\bar{V}$ , and  $E$  are seen to be quite acceptable. The calculation point out that the curve resulting from the equation (5) and represented in Fig.15-1 for integral fluxes above the  $10^{18}$  n/cm<sup>2</sup> can be expressed by the equation of the type (1), meanwhile the coefficient values of the equation (1), A and  $\phi t_0$  appear to be  $12,5 \text{ kg/mm}^2$  ( $\text{cm}^2/\text{n} \cdot 10^{-18}$ )<sup>1/3</sup> and  $4.5 \times 10^{16} \text{ n/cm}^2 \times 10^{-18}$  respectively, which agrees only too well with the data of Table II.

For the sake of comparison, making use of the value  $E = 64$  ev the calculations were made for the curves expressing the changes of the yield strength as regards the irradiation dose for the spectra of a water-water reactor of Fig.14(2) and the fission spectrum of Fig.14(3).

The normalisation condition for the three spectra is:

$$\int_0^{L,3} \psi(u) du = 5.10^{13} \text{ n/cm}^2$$

x) The spectra to be seen in Fig.8 (1 and 2) were calculated by Ju.G.Nikolayev.

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 i.e. it was assumed that the integral fluxes of neutrons of  
 > 1 Mev energy for the same irradiation time are adequate .  
 The results of the calculation are shown in Fig.9(2 and 3)  
 where from it transpires that the adequate integral neutron  
 fluxes with the energy of > 1 Mev may occasionally bring  
 about different extents of changes to occur in the yield  
 strength under irradiation in different spectra.

The authors express their sincere gratitude to M.Brumovsky,  
 V.I.Vikhrov, V.I.Karpukhin, V.N.Kuznetzov, V.P.Nikolayev,  
 for their valuable assistance in the study.

Table 1

Chemical Composition of Steels under Study

Material	Height of billets	Element contents , %									Heat treat- ment
		C	Si	Mn	Cr	Ni	Mo	Cu	W	V	
The 22 K steel	200	0.24	0.27	0.8	0.20	0.20		0.14	-	-	Normaliza- tion + temper.
The M ste- el	100	0.1	0.56	1.58	0.07	0.06	-	0.25	-	-	" -
The 22 K type steel	230	0.2	0.3	1.2	0.1	0.1	0.04	0.08	-	-	" -
The 16Г HM steel	90	0.16	0.31	1.2	0.24	1.16	0.45	0.20	-	-	" -
The 25 XHM	100	0.22	0.3	0.48	3.3	1	0.4	-	-	-	Hardening + temper.
Weld metal	200	0.07	0.8	1.4	0.05	0.1	0.05	0.1	-	-	Annealing
Weld metal	100	0.2	0.3	1.3	0.1	0.2	0.3	0.1	-	-	Annealing
Weld metal	100	0.05	0.3	0.6	0.03	0.06	-	-	-	-	Annealing

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Table II

A and B Coefficient Values for Various Materials  
and Irradiation Temperatures

Material	Irradiation temperature, °C	A kg/mm <sup>2</sup> $(n/cm^2 \cdot 10^{-18})^{1/3}$	B, °C $(n/cm^2 \cdot 10^{-18})^{1/3}$	$\frac{B}{A}$ °C kg/mm <sup>2</sup>
1. The 22K type steel	100-220	13.2	37	2.8
	185	-	40	-
	285	7.3	23.5	3.15
	330	-	9.7	-
	350	4.5	9.6	2.1
2. Welded joints of the 22K steel	100-220	12.2	-	-
	100-220	16.5	-	-
The weld area of the 22K steel	150-220	13.7	44	3.2
The weld me- tal.	150-220	12.3	50	-
	220	-	31.7	-
	375-420	-	7.4	-
3. The M type steel	150-220	-	39.5	-
	100-200	-	50	-
	250	-	38.7	-
4. The 16 ΓHM type steel	285	13.2	38	2.9
	300-350	-	15.8	-
	375-420	4.2	7.7	1.9
	450	2.95	3.5	1.2
	200	11.8	-	-
	250	-	22	-

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1	2	3	4	5
5.The 25 X3HM	250-295	-	18.4	-
type steel	320	-	13.6	-
	350	4.6	-	-
6.The 12 XMΦII	280	-	9.4	-

Note: Coefficient terms  $A \left[ \frac{\text{kg} / \text{mm}^2}{(\text{n/cm}^2 \cdot 10^{-18})^{1/3}} \right]$

$$B \left[ \frac{^{\circ}\text{C}}{(\text{n/cm}^2 \cdot 10^{-18})^{1/3}} \right]$$

Table III

The Values of the B coefficients for Various  
Samples and Testing Procedures for the 22K - type  
Steel.

Irradiation Temperature -  $130 + 220^{\circ}\text{C}$

The sample type and its dimen- sions	Testing proce- dure	Critical tempera- ture of brittle- ness in various crite- rion			B = $\frac{\Delta T}{(\phi t)^{1/3}}$ $^{\circ}\text{C}$ $(n \times \text{cm}^2 \cdot 10^{-18})^{1/3}$
		$T_{0.4}$	$T_{70\%}$	$T_{1/3}$	
1. Cylindrical $\phi 5/3 \times 55 \text{ mm}$	impact bending	-32	-	-	39.5
2. Menager 10x10x55 mm	Same	-42	+20	-	36.7
3. With reproduced crack 10x10x55 mm	Same	+35	+42	-	39.8
4. With sharp notch 10x10x55 mm	static bending	-	-	+7	33.5
5. With repro- duced crack 10x10x55 mm	Same	-	-	+17	24
6. With sharp notch 20x20 x110 mm	Same	-	-	+38	33

Note: For the Menager type samples the coefficient B is  
determined after the criterion  $T_{70\%}$ .

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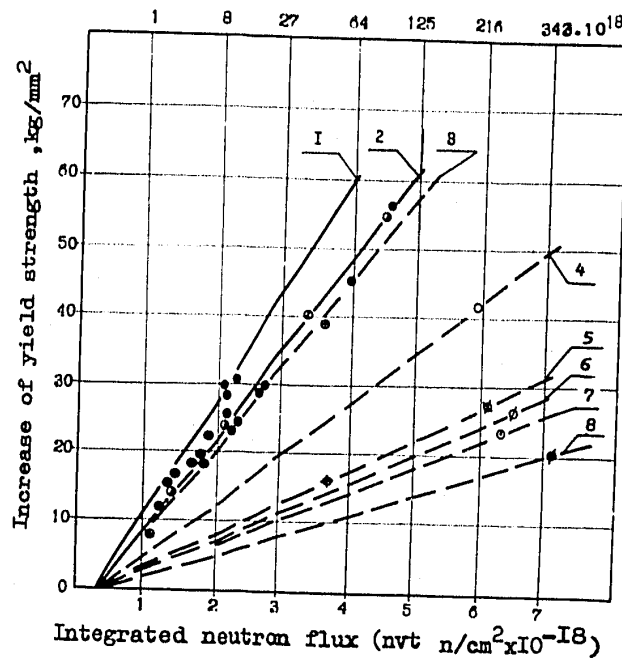


Fig. 1. The effects of integrated neutron flux and irradiation temperature on the increase of yield strength of steels. 1, 2, 3-22K, M, type 22K, 16 PHM, 25X3HM. 2-22K, 150-220°C. 4-22K, 285°C. 5-25X3HM, 375-425°C. 6-16 PHM, 425°C. 7-22K, 350°C. 8-16 PHM, 450°C.

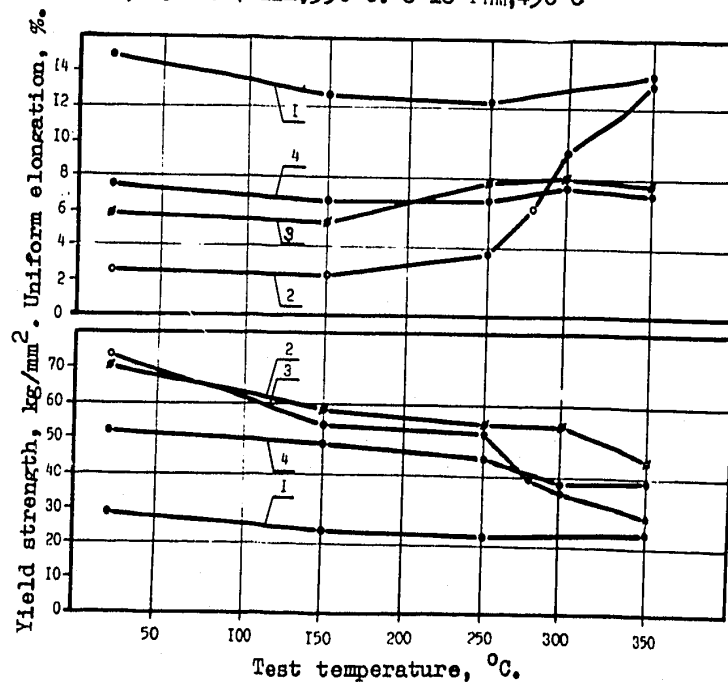


Fig. 2. The effect of test temperature on the yield strength and uniform elongation of the 22 K steel. 1- unirradiated  $2.7 \times 10^{19} \text{ n/cm}^2$ , 185°C. 3-  $2.1 \times 10^{20} \text{ n/cm}^2$ , 285°C. 4-  $2.5 \times 10^{20} \text{ n/cm}^2$ , 350°C.

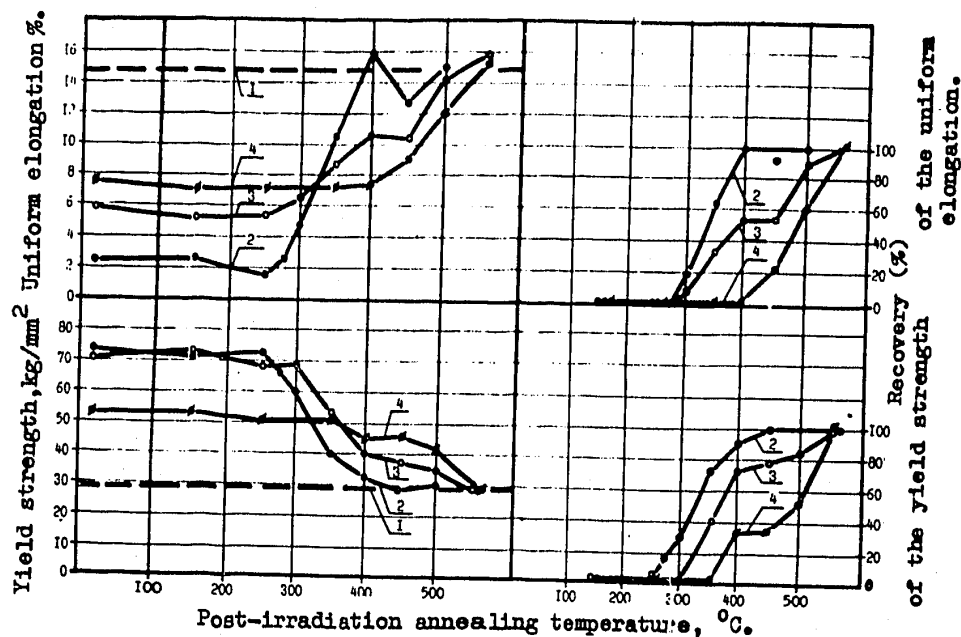


Fig.3. The effect of post-irradiation annealing temperature on the recovery of the yield strength and uniform elongation of the 22 K steel  
 1- unirradiated. 2-  $7 \times 10^{19} \text{ n/cm}^2$ ,  $185^\circ\text{C}$ . 3-  $2 \times 10^{20} \text{ n/cm}^2$ ,  $285^\circ\text{C}$ .  
 4-  $2.5 \times 10^{20} \text{ n/cm}^2$ ,  $350^\circ\text{C}$ .

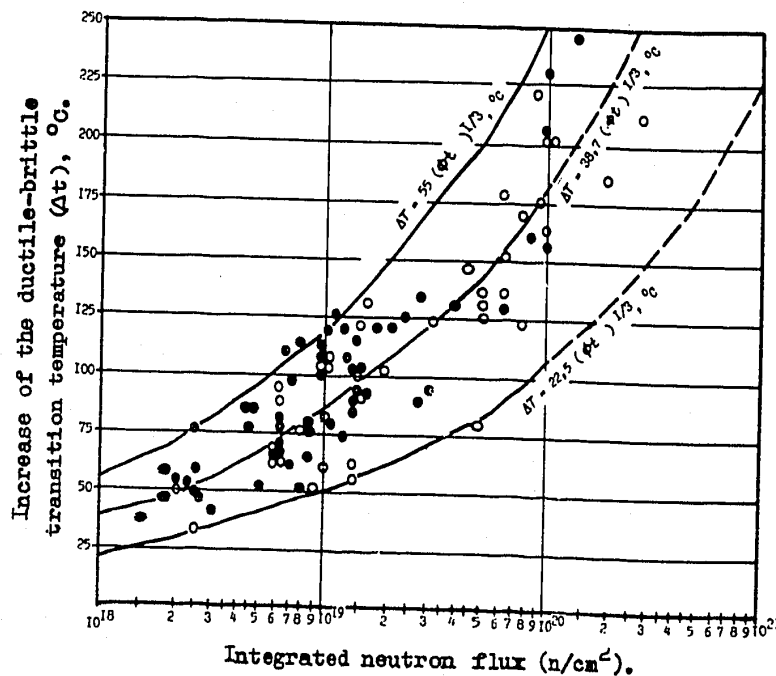


Fig.4. The effect of integrated neutron flux on the increase of the ductile-brittle transition temperature of the 22K and M type steels and their welded joints.  
 The irradiation temperature -  $130-220^\circ\text{C}$ . Cylindrical (diameter of 5mm, depth of notch 1mm with radius by notch 0.25mm) and Menage type specimens.

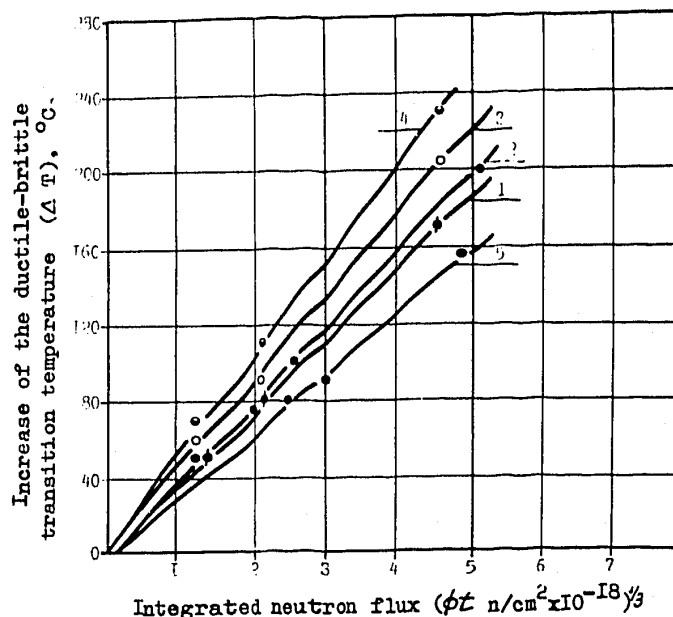


Fig.5. The effect of the irradiation dose on the increase ductile brittle transition temperature. The irradiation temperature - 130-220°C. 1-the 22K type steel. 2- the M-type steel. 3- the heat affected zone of the 22K type steel welded joint. 4- the weld metal of the 22K type steel. 5- the weld metal of the steel of the 22K type steel.

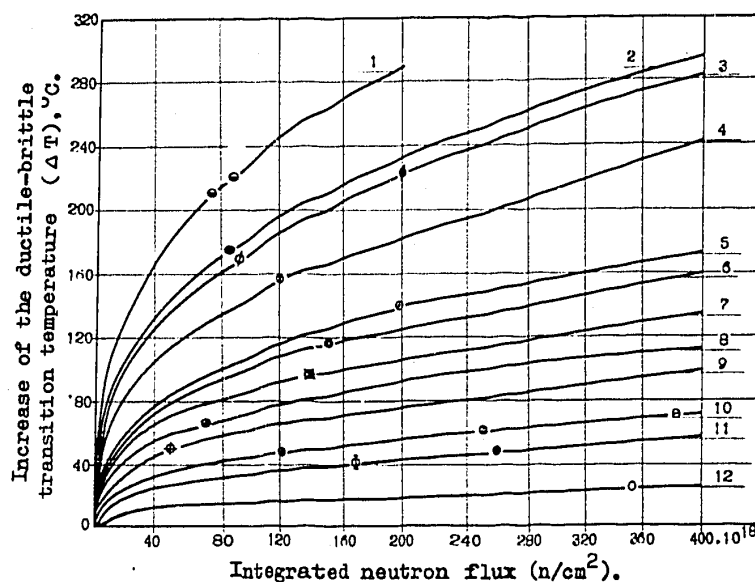


Fig.6. The effect of the integrated neutron flux and irradiation temperature on the  $\Delta T$  of some steels. 1-I6 HM, 200°C. 2-22K, 185°C. 3- I6 PHM, 265°. 4- the weld metal of the 22K type steel, 220°C. 5- 22K, 285°C. 6-25X3HM, 250°C. 7-25X3HM, 295°C. 8-I6 PHM, 350°C. 9- 25X3HM, 320°C. 10-I2X2M A, 280°C and 22K, 350°C. 11-the weld metal of 22K type steel, and I6 PHM 375-420°C. 12-I6 PHM, 450°C

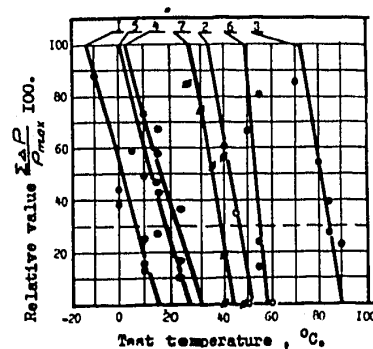


Fig. 7. The effect of test temperature on the relative value  $\frac{\sigma}{\sigma_{max}} \cdot 100$  of 22K type steel  
 1, 5, 7-unirradiated. 2- $2 \times 10^{18}$  n/cm<sup>2</sup>, 200\$^\circ\$C. 3-  $1 \times 10^{19}$  n/cm<sup>2</sup>, 200\$^\circ\$C.  
 4-  $7.3 \times 10^{18}$  n/cm<sup>2</sup>, 155\$^\circ\$+300\$^\circ\$, 3 hr. 6-4,  $1 \times 10^{18}$  n/cm<sup>2</sup>, 150\$^\circ\$C.  
 7-specimens with dimensions of 20x20x110 mm with a sharp notch.  
 1, 2, 3, 4 - the specimens with dimension of 10x10x55 mm with a sharp notch. 5, 6 - the specimens with the reproduced cracks (produced by Drozdovsky's method).

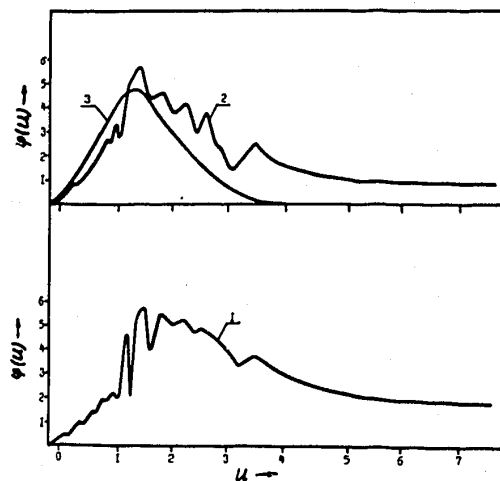


Fig. 8. The calculated neutron spectra for:  
 1. The PFR type reactor; 2. the WWR type reactor;  
 3. the fission spectrum.

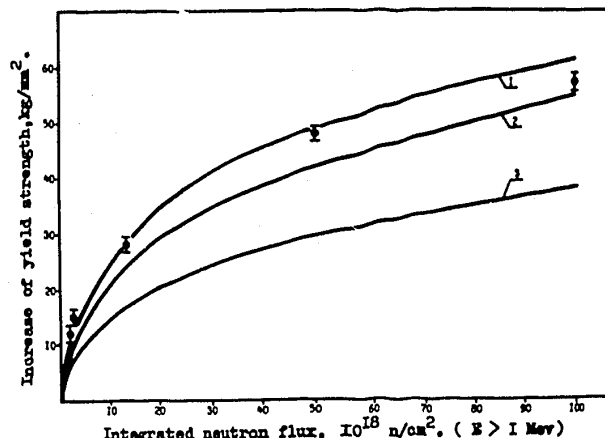


Fig. 9. The change of the yield strength as function of integrated neutron flux  
 1. The PFR type reactor; 2. the WWR type reactor; 3. the fission spectrum type reactor (steady lines are the calculated data, the experimental values of yield strength for a mild steel have obtained after irradiation of this steel (at the PFR reactor).